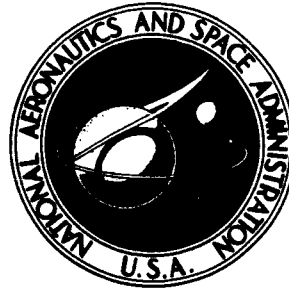


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ROLLING-CONTACT STUDIES WITH FOUR REFRACTORY MATERIALS TO 2000° F

by Richard J. Parker, Salvatore J. Grisaffe,
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Lewis Research Center,
Cleveland, Ohio

TECHNICAL PREPRINT prepared for Eleventh Joint
International Lubrication Conference sponsored by
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ABSTRACT

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Four refractory materials were tested in the NASA five-ball fatigue tester to study their behavior under repeated stresses applied in rolling contact: hot-pressed alumina, cold-pressed-and-sintered alumina, self-bonded silicon carbide, and nickel-bonded titanium carbide cermet. The failures that developed in all four materials were shallow, eroded areas of apparent surface origin unlike fatigue spalls found in bearing steels. The load capacity of hot-pressed alumina was the highest of the four materials tested but was only about 7 percent of that of a typical bearing steel. Preliminary tests at elevated temperatures indicated that hot-pressed alumina is capable of rolling-contact operation at temperatures up to 2000° F without gross wear or plastic deformation.

INTRODUCTION

Aerospace technology dictates a need for bearings to operate reliably at temperatures to 2000° F. Since the temperature range between 700° and 2000° F is beyond the range in which current ferrous and nonferrous bearing materials are capable of operating, the more refractory materials and compounds must be considered. Among these materials are alumina, titanium carbide cermets, and silicon carbides (ref. 1). A relatively large amount of research and development has been performed with alumina and titanium carbide cermets in rolling-element bearings. Considerably fewer data,

however, have been reported on the use of silicon carbide for this purpose.

Data reported in references 2 and 3 indicate that in both sliding and rolling contact at temperatures to 1200° F alumina exhibits friction and wear characteristics somewhat similar to those of conventional bearing steels over the same temperature range. Additionally, the coefficient of friction of alumina sliding unlubricated on several materials at temperatures up to 1600° F is comparable with that of M-2 steel sliding unlubricated on the same materials at temperatures to 1000° F (ref. 2).

Fused alumina balls (96.0 percent Al_2O_3) were run unlubricated under oscillatory motion on several plate materials at temperatures from 600° to 1200° F and at maximum Hertz stresses from 637,000 to 1,012,000 psi (ref. 3). The wear on all tests was light, but in some tests the balls fractured. Fracture at such severe stresses would, however, not be unexpected.

In reference 4 the data indicated that a 20-millimeter-bore titanium carbide cermet ball bearing was capable of running to temperatures of 1200° F for periods of 2 to 3 hours at DN values of approximately 1/2 million with a solid film lubricant. Additional research reported in reference 5 indicated that titanium carbide cermet exhibited friction coefficients comparable with those of alumina sliding unlubricated on similar materials to temperatures up to 1650° F. Also, development work was reported in reference 6 with a bearing having titanium carbide races and alumina balls run at moderate loads with molybdenum disulfide lubricant carried in an inert gas. These bearings operated at temperatures to 1500° F for periods as long as 8 hours. Failure of these bearings was by pitting of the titanium carbide races.

Unlubricated rolling-contact bench tests reported in reference 7 indicated that a self-bonded silicon carbide exhibited minimal wear relative to other materials reported therein at a maximum Hertz stress of 375,000 psi for over 250 million stress cycles of operation. Macroscopic examination of the wear track revealed no surface cracking or spalling. In addition, research reported in reference 8 indicated that a titanium carbide - silicon carbide combination resulted in approximately the same sliding friction coefficients as that of a titanium carbide - alumina combination.

In view of the reported literature on the friction and wear properties of these materials, they are possible materials for rolling-element bearings at temperatures of 1600° F (and possibly higher). The object of the research described herein, which is based on the work reported initially in references 9 and 10, was therefore (1) to investigate the effects of temperature and stress on the surface failure of hot-pressed alumina, cold-pressed-and-sintered alumina, self-bonded silicon carbide, and nickel-bonded titanium carbide cermet ball specimens under repeated stresses applied in rolling contact; (2) to determine experimentally the stress-life relation of these materials; (3) to determine experimentally the load-carrying capacity of these materials; and (4) to investigate initially the operation of these materials at temperatures to 2000° F. The data obtained in this investigation are compared with data for steel ball specimens. All experimental results for a given type of material were obtained with the same batches of material and lubricant.

DESCRIPTION OF MATERIALS

The four materials investigated were selected on the basis of their high-temperature properties: hot-pressed alumina (Al_2O_3), cold-pressed-and-sintered alumina, self-bonded silicon carbide, and nickel-bonded titanium carbide. Specimens of each material were fabricated into rough blanks and finished to 1/2-inch-diameter ball specimens of grade 25 specification (0.000025-in. sphericity; 0.000050 in.-uniformity) for testing.

Average data on the physical characteristics for each material are given in table I. A description of the ball specimen of each material tested follows.

Hot-Pressed Alumina

The hot-pressed alumina balls were dark gray and exhibited some randomly distributed darker streaks and spots. The major impurities present in the 99-percent-pure alumina were magnesium, silicon, and iron, which produced a complex spinel phase with a lattice parameter similar to that of nickel aluminate. This material contained about 0.6 volume percent pores; its surface finish was 0.3 to 0.5 microinches rms. A typical photomicrograph of the hot-pressed alumina is shown in figure 1(a).

Cold-Pressed-and-Sintered Alumina

The balls made of the 99-percent-pure cold-pressed-and-sintered alumina material ranged in color from white to cream because of small amounts of magnesium, calcium, and silicon impurities. On the basis of color alone, the balls, all from "the same batch," could be seen not to

be of uniform composition. Further examination of these balls indicated that the surface of the as-received specimens showed a roughness of from 3 to 8 microinches rms. This relatively poor surface was the result of 4.3 volume percent pores in the material as can be observed in the photomicrograph (fig. 1(b)).

Self-Bonded Silicon Carbide

Ideally, the self-bonded silicon carbide is fabricated from a mixture of carbon and silicon carbide that, when exposed to silicon vapor, is transformed into 100-percent silicon carbide. The material supplied, however, contained about 12 volume percent of unreacted silicon, which was present as large irregularly shaped white areas concentrated at grain boundaries and corners of the gray silicon carbide matrix (see fig. 2). The surface finish of this material was also relatively poor and ranged from 2 to 6 microinches rms.

Nickel-Bonded Titanium Carbide Cermet

The nickel-bonded titanium carbide cermet contained about 71 volume percent of hard titanium carbide uniformly dispersed in a matrix of ductile nickel. This material was very dense (no visible porosity) and was extremely homogeneous, as is shown in figure 3. These latter factors were promoted by several percent of molybdenum present in solid solution in the nickel matrix to facilitate wetting of the carbide particles. The even dispersoid distribution combined with some smearing of the matrix during grinding resulted in a very smooth surface, 0.6 to 0.8 microinches rms.

For the sake of brevity, the materials will hereinafter be designated cold-pressed alumina, hot-pressed alumina, silicon carbide and titanium-

carbide cermet.

APPARATUS AND PROCEDURE

Rolling-contact life tests were conducted with 1/2-inch-diameter balls of each of the four refractory materials in the five-ball fatigue tester described in detail in reference 11. Figure 4(a) is a section view of this tester. The test assembly (fig. 4(b)) consisted of a test specimen pyramided upon four lower support balls, positioned by a separator, and free to rotate in an angular contact raceway. Specimen loading and drive were applied through a vertical spindle that has notched at its lower end to fit a tongue cut in the test specimen.

Tests were performed at a shaft speed of 950 rpm, a contact angle of 20° , race temperatures of 80° and 700° F, and with a lubricant mist of a highly refined naphthenic mineral oil. The support balls were made of SAE 52100 for the 80° F tests and AISI M-50 for the 700° F tests. Step-load tests at the previously stated conditions were made with each material to determine the stresses at which these specimens could be tested to produce a failure within a reasonable time. In order to determine the stress-life relation for each material, three or four stresses were chosen for life tests at 80° F with each material. An intermediate stress was chosen for each material for tests at 700° F.

The life data were treated statistically according to the methods of reference 12 and plotted on Weibull coordinates. (Weibull coordinates have an ordinate that is the log-log of the reciprocal of the probability of survival and is graduated in statistical percent of specimens failed. The abscissa is the log of the life. Failure data fitting a Weibull distribution and plotted on these coordinates are

represented by a straight line.)

Immediately prior to testing, the test specimens were inspected at a magnification of 15 diameters, and the size and number of initial surface pits in the running track area, if any, were recorded. During a test, periodic inspections of the test-specimen running track were made at a magnification of 15 diameters, and observations were recorded. The time interval between inspections varied with the stress level at which the test was run and with the observed rate of growth of a failure pit. A specimen was considered failed when a pit reached the full width of the running track.

A modified five-ball tester (fig. 4(c)) was used in tests at temperatures between 1100° and 2000° F and is described in detail in reference 9. Operating temperatures to 2000° F were maintained by induction heating coils around the test housing. Tests were performed at a shaft speed of 450 rpm, at a contact angle of 20°, at maximum Hertz stresses of 270,000 to 550,000 psi, and with molybdenum disulfide - argon mist lubrication. Support balls used in these tests were 1/2-inch-diameter hot-pressed alumina. Testing and inspection procedures for these tests were similar to those of 80° and 700° F tests.

ROLLING-CONTACT LIFE RESULTS

Effect of Stress

Rolling-contact life tests were conducted with hot-pressed alumina, cold-pressed alumina, silicon carbide, and titanium carbide cermet ball specimens in the five-ball fatigue tester described previously. The life results of tests at 80° F are shown in figure 5. The 10- and 50-percent lives are tabulated in table II. The life results show an

expected decrease in life with increasing contact stress.

Plots of the logarithm of stress against the logarithm of the 10- and the 50-percent lives for these four materials are shown in figure 6. These plots show that life varies inversely with stress to a power ranging from 9.4 to 10.8 for hot-pressed alumina, from 6.0 to 8.1 for cold-pressed alumina, from 6.9 to 8.6 for silicon carbide, and from 9.7 to 10.5 for titanium carbide cermet. A commonly accepted range for this exponent for bearing steel is from 9 to 10. The hot-pressed alumina and the titanium carbide cermet, therefore, show about the same sensitivity to stress as that which is usually associated with bearing steels. The cold-pressed alumina and the silicon carbide appear less sensitive to stress than bearing steels.

A major difference among the four materials was the surface finish of the ball specimens (0.3 to 0.8 μ in. rms on the hot-pressed alumina and the titanium carbide cermet and 2.0 to 8.0 μ in. rms on the cold-pressed alumina and the silicon carbide). The surface pits and irregularities on the cold-pressed alumina and the silicon carbide may cause such high stresses to exist in the zone of contact that the effect of increased stress due to a nominal increase in load (table II) is minimized; that is, the actual contact stress on these materials may not be changed to the extent that calculations show for a given change in normal load. The effect would be an apparent stress sensitivity or stress-life exponent less than that of a material with a better surface finish.

Effect of Temperature

Rolling-contact tests were conducted with the materials at temperatures of 700° to 2000° F. The results of the 700° F tests are plotted on

Weibull coordinates in figure 7 and are tabulated in table II. Figure 7 also shows the experimental lives at 80° F (at the same stress).

The accepted relation between life L and lubricant viscosity μ is $L = K\mu^n$, where K is a constant and n equals 0.2 to 0.3 (refs. 13 and 14). If the 80° F lives were adjusted to 700° F by the relation

$$\frac{L_{80}}{L_{700}} = \left(\frac{\mu_{80}}{\mu_{700}} \right)^n$$

then the lives within the range indicated in figure 7 would be expected. The experimental lives at 700° F for these materials either fall within or are close to this predicted range with the exception of silicon carbide. Although the viscosity-life relation was obtained in fatigue tests with steels where the failures were largely subsurface in origin, the relation appears to apply to the surface-failure life in these materials. The shorter lives exhibited at 700° for these materials may thus be accounted for by changes in the viscosity of the lubricant. For the silicon carbide, which exhibited a life at 700° F considerably higher than the predicted range, the effect of surface pits and irregularities on these specimens may minimize the effect of a lubricant viscosity change due to increased temperature.

Three of the four refractory materials were run in a modified five-ball fatigue tester to temperatures of 2000° F with molybdenum disulfide - argon mist lubrication. The results of these preliminary tests indicated that the hot-pressed alumina is capable of operating to temperatures of 2000° F. Tests with cold-pressed alumina and silicon carbide at 2000° F and stresses as low as 270,000 psi, however, resulted

in a general track deterioration unlike the failure pits observed at 80° and 700° F. Titanium carbide cermet, at temperatures beyond 1100° F and a maximum Hertz stress of 310,000 psi, exhibited excess cumulative plastic deformation, which indicated that the value of this material is limited to less-severe conditions of temperature and stress.

Surface-failure data with hot-pressed alumina tested at 2000° F and a maximum Hertz stress of 550,000 psi is given in figure 8 and tabulated in table II. The experimental lives at 80° and 700° F (at the same stress) but with a mineral-oil lubricant are also presented to provide a relative indication of the performance of hot-pressed alumina at 2000° F.

Load Capacity

Since the four materials were tested at different stresses, a direct comparison of lives was not made. Bearing materials are frequently compared on the basis of load capacity (the contact load in pounds that will produce failure of 10 percent of the group of test specimens in 1 million stress cycles). The experimental capacities of these four materials are tabulated in table II. The average capacity at 80° F of 1/2-inch-diameter balls was 31 pounds for hot-pressed alumina, 4.3 pounds for cold-pressed alumina, 5.6 pounds for silicon carbide, and 12.6 pounds for titanium carbide cermet. These data were compared with the capacity of a typical vacuum-melt M-1 bearing steel, which was tested under similar conditions and which exhibited a capacity of about 450 pounds. At 80° F the hot-pressed alumina thus had a capacity approximately 7 percent of that of the M-1 steel. The capacity of the titanium carbide cermet was approximately

3 percent, while that of the silicon carbide and the cold-pressed alumina were approximately 1 percent that of the bearing steel.

As previously discussed for the life results, a decrease in load capacity was observed when the temperature was increased from 80° to 700° F. This decrease, as previously discussed, is believed to result from the decrease in lubricant viscosity due to increase in temperature.

OBSERVATIONS AND DISCUSSION FOR MATERIALS

The progression of an incipient failure into a full-track-width pit was a slow process that frequently consumed half of the total running time of the ball specimens. A typical failure pit for each of the four materials tested at 80° F is shown in figure 9. The depth of the failure pits was about 0.001 inch for all materials except for the silicon carbide pits, which were from 0.003 to 0.005 inch deep. In general, the failures at 700° F were similar to those at 80° F.

The failure in each material is discussed briefly. These discussions represent possible failure mechanisms. Exact establishment of the mode of failure requires extensive electron microscopy studies, which are beyond the scope of this presentation.

Hot-Pressed Alumina

It is generally accepted that cracks nucleate more readily at free surfaces than they do within the volume of a material. This concept is substantiated by the reductions in fatigue strength that occur when the surface roughness of steel specimens is increased (ref. 15). In brittle materials such a surface sensitivity is magnified many times

since plastic flow cannot occur to relieve localized stresses.

It is also well known that the strength of a brittle material is dependent on its porosity (size, shape, and distribution of pores; ref. 16).

The hot-pressed alumina, as was pointed out previously, contained a uniform dispersion of pores (0.6 volume percent) and a rather smooth surface (0.3 to 0.5 μ in. rms). The failure of these balls under rolling contact may be expected to occur by small cracks, nucleated at surface pores and propagating into the interior until they reach another pore. Internal pores can serve both as crack nuclei and as crack terminators (as a drilled hole in a glass window stops a crack). Failure is thus a rather slow process that involves time to nucleate and to propagate a crack and for several cracks to undermine a small volume of the running track until it is lost. Since the alumina was essentially in the elastic range over the entire testing schedule, failures at all temperatures should be similar.

Cold-Pressed-and-Sintered Alumina

The higher porosity of the cold-pressed-and-sintered alumina resulted both in decreased strength and in a poorer surface finish. Both factors contributed to the decreased resistance of this material to failure as compared with the more dense hot-pressed alumina. In general, the same type of failure mechanism can be anticipated for cold-pressed alumina as was described for hot-pressed alumina.

Self-Bonded Silicon Carbide

Self-bonded silicon carbide contains approximately 12 volume percent of silicon, which is soft and has a low modulus of elasticity.

These irregular particles of silicon come out of the hard, brittle silicon carbide during testing and leave sharp notches in the matrix, where brittle fracture could occur. This process was aided by pre-existing surface notches (pits) believed to result from silicon removal during fabrication.

Nickel-Bonded Titanium Carbide

The nickel - titanium carbide cermet involves a ductile matrix in which 71 volume percent of fine, evenly divided carbide particles are uniformly dispersed.

Dislocations can move easily in the nickel matrix, even at the lower testing temperatures. When a dislocation passes between obstacles such as the dispersed carbide particles, a dislocation loop encircling the obstacle is left behind. Subsequent dislocations encounter ever increasing resistance (i.e., back stress) until a point is reached at which the required shear stress for deformation exceeds the shear stress of the particle or the matrix. This material probably experienced failures in the carbide particles because of the high volume fraction of this phase present.

At elevated temperatures the strength of the nickel matrix decreases rapidly until severe plastic deformation occurs at about 1100° F. This material is thus unsuited for consideration as a rolling-contact element under the stresses investigated.

General Comments

The ability of a ceramic or cermet material to be functional in rolling-contact applications appears to be related to its physical properties and to its surface condition. Consequently, surface

finish appears to be an important criterion for long life. Since surface finish was related to the amount of porosity or to the presence of a weak second phase, such conditions should be avoided for proposed high-temperature bearing materials.

On the basis of this investigation present day ceramic fabrication techniques appear to be unable to supply high-quality material for rolling elements for high-temperature application. As ceramic materials approach homogeneity and zero porosity, however, high-temperature bearing reliability and load capacity should increase.

SUMMARY OF RESULTS

Surface failure tests in rolling contact were conducted in the NASA five-ball fatigue tester with four refractory materials: hot-pressed alumina, cold-pressed-and-sintered alumina, and self-bonded silicon carbide, and nickel-bonded titanium carbide cermet. These tests were performed at a contact angle of 20° , a shaft speed of 950 rpm, race temperatures of 80° and 700° F, and maximum Hertz stresses of 250,000 to 650,000 psi and with a highly refined mineral-oil lubricant. Support balls were SAE-52100 and AISI M-50 steel in the 80° and the 700° F tests, respectively. Preliminary tests were also performed with each of the four refractory materials at temperatures from 1100° to 2000° F. Hot-pressed alumina support balls were used with molybdenum disulfide lubrication in a modified five-ball tester. The following results were obtained:

1. The failure pits in all four materials were shallow, eroded areas of apparent surface origin and were unlike fatigue pits found in bearing steels.

2. Progression of an incipient failure for all four materials was a slow process that frequently consumed one-half of the total running time of the specimen.

3. The lives of hot-pressed alumina and nickel-bonded titanium carbide cermet varied inversely with stress to an average power of approximately 10. The cold-pressed-and-sintered alumina and the self-bonded silicon carbide, however, were less sensitive and exhibited an average stress-life exponent of approximately 7.

4. The capacity at 80° F of hot-pressed alumina was about 7 percent that of a typical bearing steel but was the highest of the four materials studied.

5. Preliminary tests at elevated temperatures indicated that hot-pressed alumina is capable of rolling-contact operation at temperatures up to 2000° F without gross wear or plastic deformation.

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TABLE I. - AVERAGE PHYSICAL PROPERTY DATA
OF REFRACTORY MATERIALS

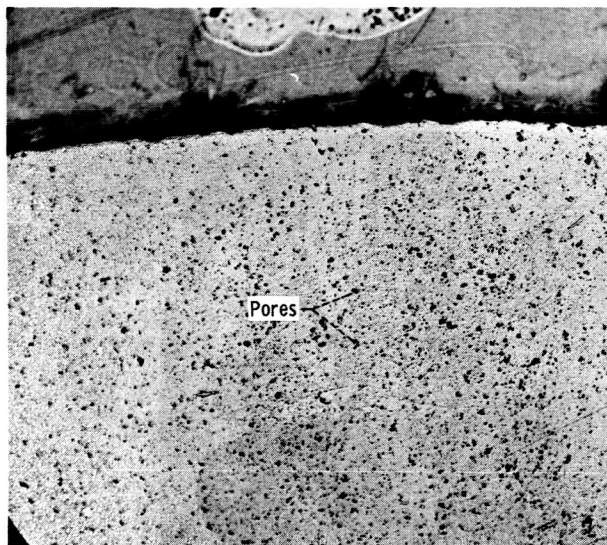
Property	Temperature	Alumina	Self-bonded silicon carbide	Nickel-bonded titanium carbide cermet
Compressive strength, psi	70 1200 2012	427,000 ----- 85,000	150,000 ----- -----	450,000 296,000 -----
Modulus of elasticity, psi	70 1600 2012 2200	52.4×10^6 ----- $\sim 41 \times 10^6$ -----	69×10^6 ----- ----- 49×10^6	57×10^6 48×10^6 ----- -----
Poisson's ratio	70	0.26	0.183	0.20
Hardness	70 1400	2000 (Knoop 100-G scale) -----	2740 (Knoop 100-G scale) -----	89 (Rockwell A) 74 (Rockwell A)
Melting point, °F	----	3659 to 3723	4680 (sublimes at $T > 3600^\circ \text{F}$)	TiC: 5700 Ni: 2647

TABLE II. - LIFE AND LOAD-CAPACITY RESULTS WITH BALL SPECIMENS
OF FOUR REFRACTORY MATERIALS

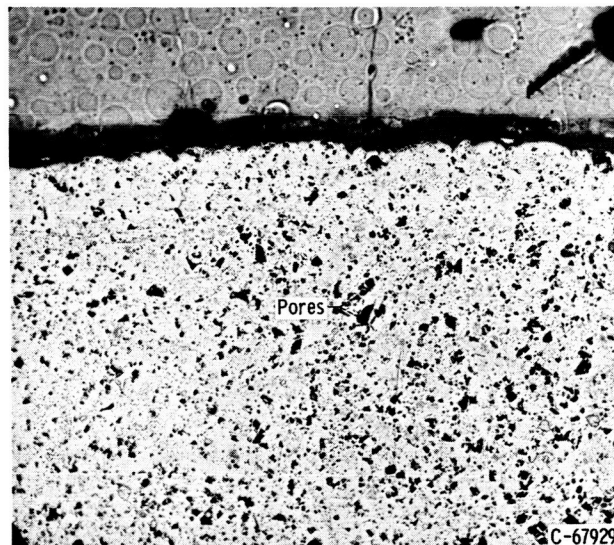
[Shaft speed, 950 rpm; contact angle, 20 ; lubricant, mineral oil.]

Material	Maximum Hertz stress, psi	Race temper- ature, °F	Ten- percent life, stress cycles	Fifty- percent life, stress cycles	Ball normal load, lb	Load capacity, lb
Hot- pressed alumina	500,000	80	2.3×10^6	5.0×10^6	24.1	31.3
	550,000	80	.66	1.33	32.1	28.1
	600,000	80	.50	1.42	41.8	33.5
	650,000	80	.19	.30	53.2	31.3
	550,000	700	.15	.32	32.1	17.5
	550,000	^a 2000	.045	.083	21.5	8.0
Cold- pressed and sintered alumina	250,000	80	2.05×10^6	7.1×10^6	3.02	4.3
	300,000	80	.72	1.59	5.21	4.4
	350,000	80	.27	.48	8.28	4.3
	300,000	700	.052	.21	5.21	1.2
Self-bonded silicon carbide	300,000	80	1.75×10^6	4.7×10^6	4.48	5.7
	350,000	80	.54	2.1	7.00	5.4
	400,000	80	.24	.43	10.6	5.7
	350,000	700	.28	.69	7.00	4.1
Nickel- bonded titanium carbide cermet	400,000	80	1.5×10^6	5.6×10^6	11.7	13.1
	450,000	80	.19	.72	16.8	10.4
	550,000	80	.064	.20	30.5	14.3
	400,000	700	.39	1.65	11.7	8.9

^aTest run in modified five-tester at 450 rpm with molybdenum disulfide - argon mist lubrication.



(a) Hot-pressed alumina.



(b) Cold-pressed alumina.

Figure 1. - Section of alumina ball specimen. X50.

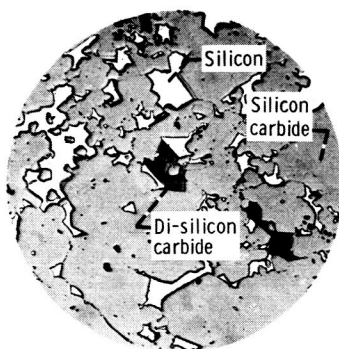


Figure 2. - Microstructure of self-bonded silicon carbide ball specimen. X125.

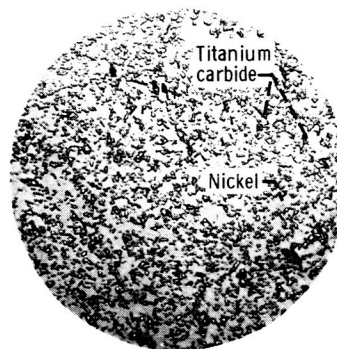
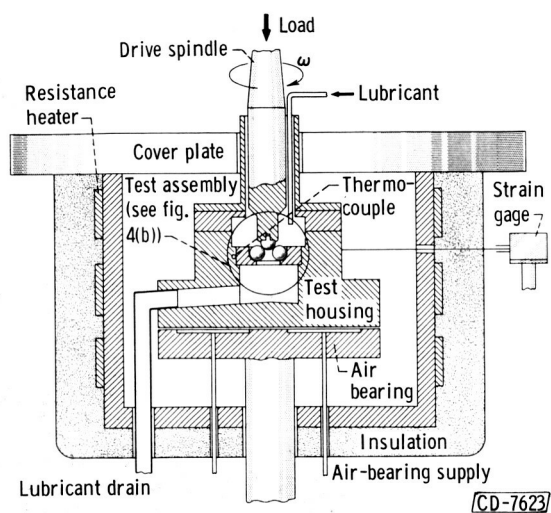
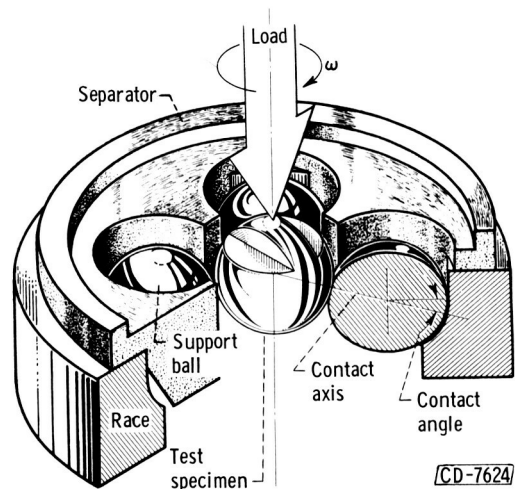


Figure 3. - Microstructure of nickel-bonded titanium carbide cermet ball specimen. X250.

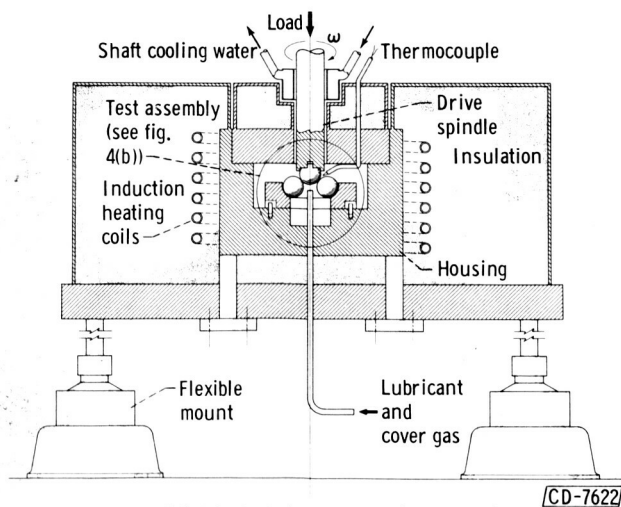


(a) Section view showing air-bearing support.



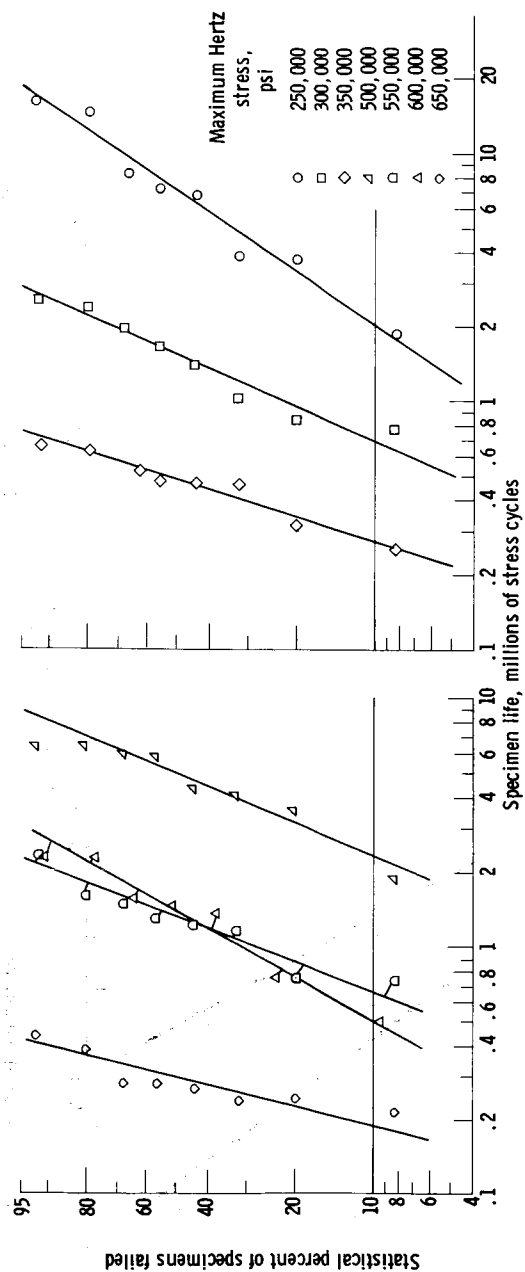
(b) Test assembly.

Figure 4. - Five-ball fatigue tester.



(c) Modified for tests between 1100° and 2000° F.

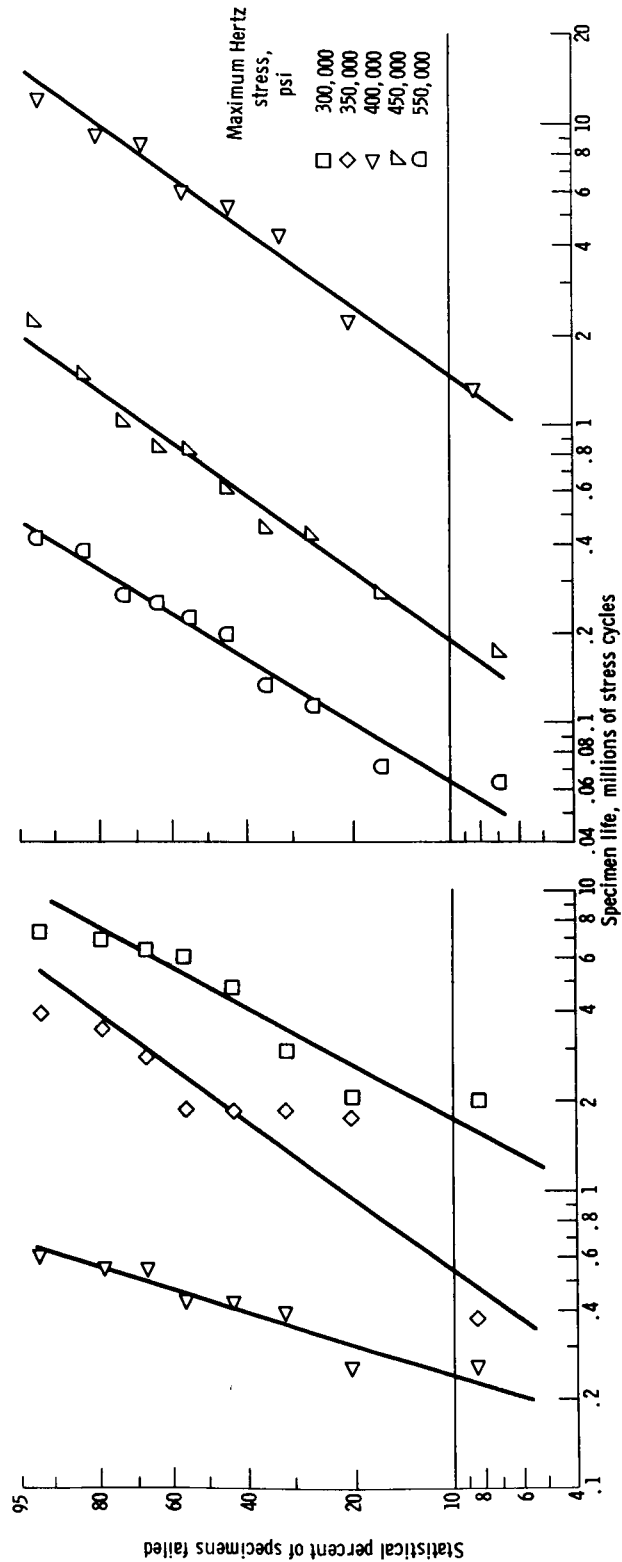
Figure 4. - Concluded. Five-ball fatigue tester.



(a) Hot-pressed alumina.

(b) Cold-pressed alumina.

Figure 5. - Rolling-contact life of 1/2-inch-diameter ball specimens of four refractory materials in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; race temperature, 80° F; lubricant, mineral oil.



(c) Self-bonded silicon carbide.

(d) Nickel-bonded titanium carbide cermet.

Figure 5. - Concluded. Rolling-contact life of 1/2-inch-diameter ball specimens of four refractory materials in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; race temperature, 80° F; lubricant, mineral oil.

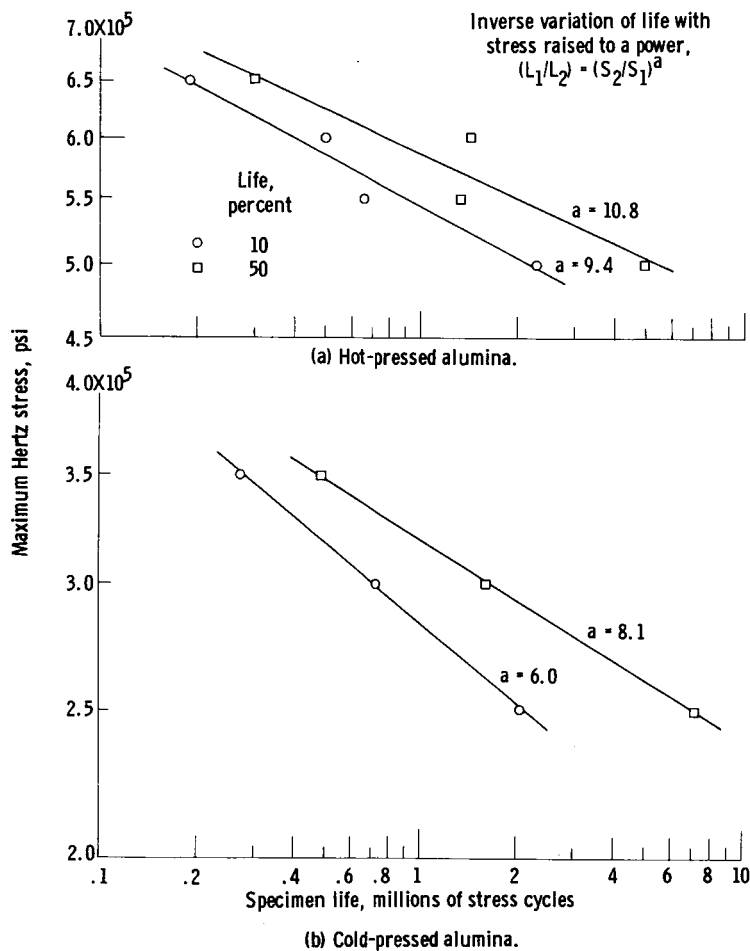


Figure 6. - Stress-life relation of 1/2-inch-diameter ball specimens of four refractory materials in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; race temperature, 80° F; lubricant, mineral oil.

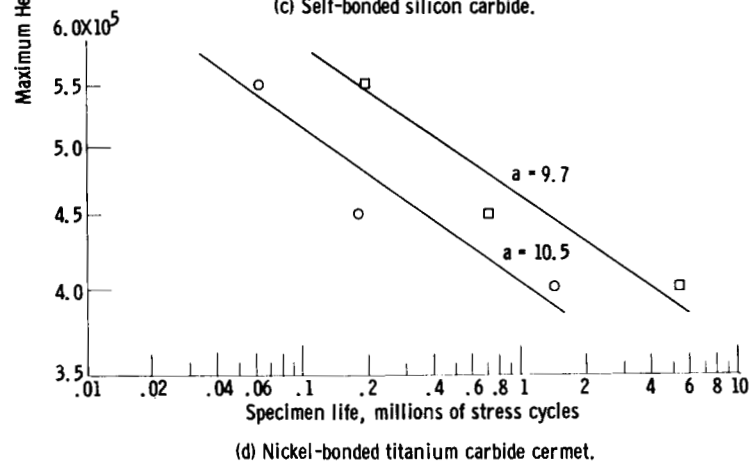
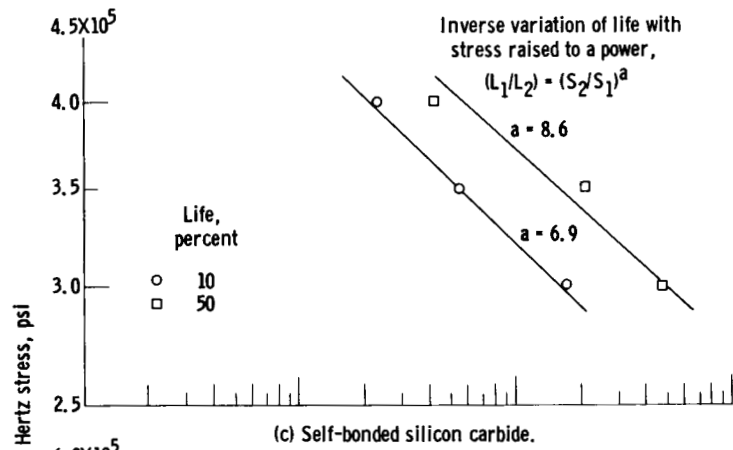
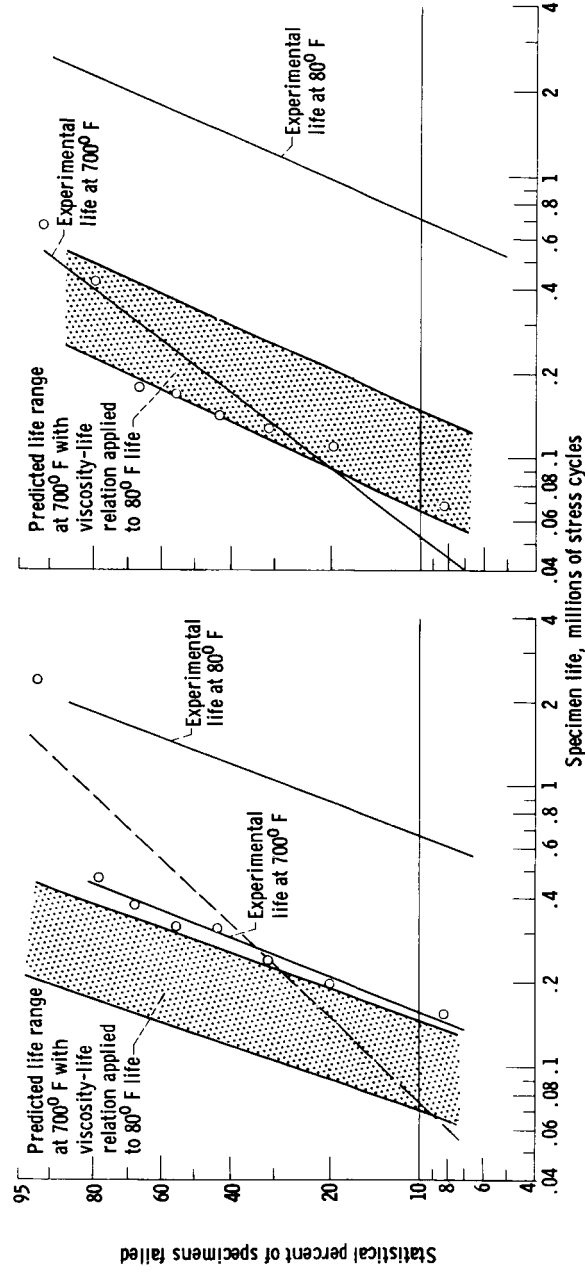
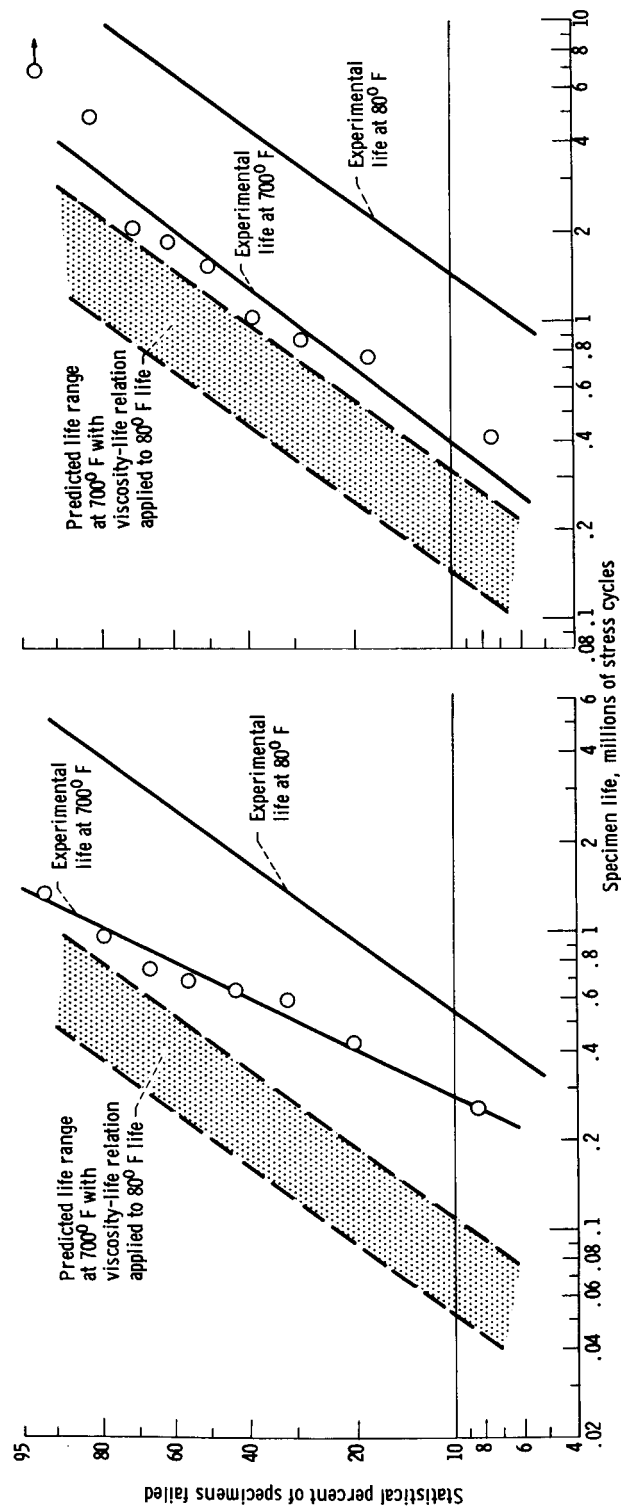


Figure 6. - Concluded. Stress-life relation of 1/2-inch-diameter ball specimens of four refractory materials in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; race temperature, 80° F; lubricant, mineral oil.



(a) Hot-pressed alumina. Maximum Hertz stress, 550,000 psi. (b) Cold-pressed alumina. Maximum Hertz stress, 300,000 psi.

Figure 7. - Effect of 700°F race temperature on life of 1/2-inch-diameter ball specimens of four refractory materials in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; lubricant, highly refined naphthenic mineral oil; viscosity at 80°F, 150 centistokes; viscosity at 700°F, 0.6 centistoke.



(c) Self-bonded silicon carbide. Maximum Hertz stress, 350,000 psi.
 (d) Nickel-bonded titanium carbide cermet. Maximum Hertz stress, 400,000 psi.
 Figure 7. - Concluded. Effect of 700° F race temperature on life of 1/2-inch-diameter ball specimens of four refractory materials in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; lubricant, highly refined naphthenic mineral oil; viscosity at 80° F, 150 centistokes; viscosity at 700° F, 0.6 centistoke.

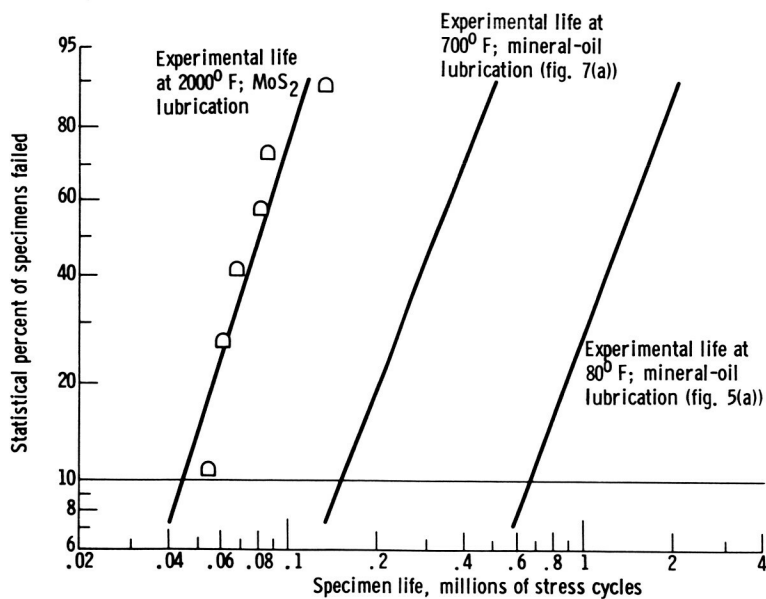


Figure 8. - Rolling contact life of hot-pressed alumina ball specimens at 2000°F in modified five-ball tester. Shaft speed, 450 rpm; contact angle, 20°; lubricant, molybdenum disulfide - argon mist; maximum Hertz stress, 550,000 psi.

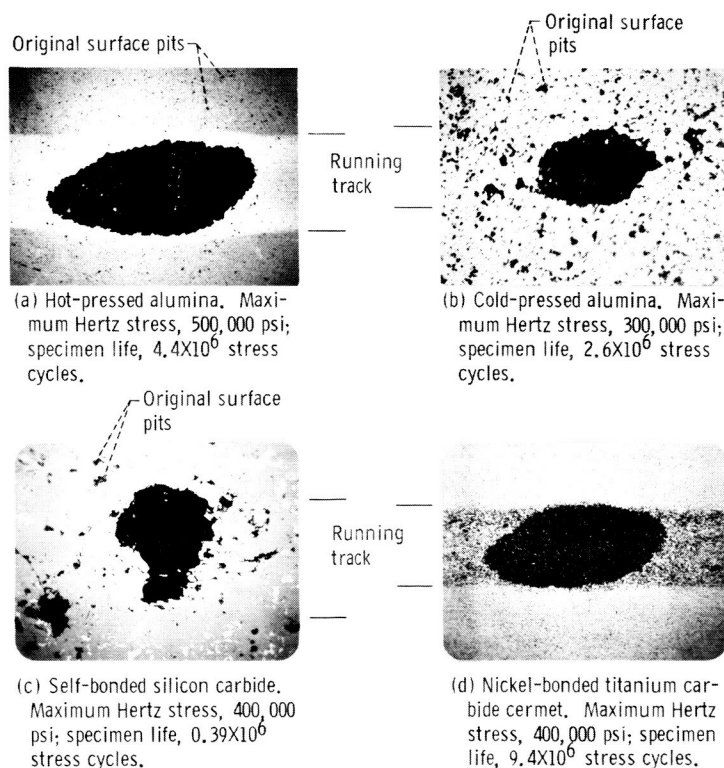


Figure 9. - Typical failure pits on 1/2-inch-diameter ball specimens of four refractory materials tested in five-ball fatigue tester. X38. Race temperature, 80°F; contact angle, 20°; shaft speed, 950 rpm.